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Wave Setup on a Sloping Beach

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B.S.

by

John R. Lesnik

COASTAL ENGINEERING TECHNICAL AID NO. 77-5

SEPTEMBER 1977

U.S. ARMY, CORPS OF ENGINEERS

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This report combines the material previously presented in Sections 2.62 and 3.85 of the Shore Protection Manual. Computation of wave setup on beaches as steep as 1 on 10 (m=0.01) can be easily determined by graphical means when incident wave conditions are defined. Practical applications are discussed and two example problems are provided.

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PREFACE

This report describes a method of estimating wave setup for beaches of varying slope. The technical guidelines presented are a combination of procedures discussed in the Shore Protection Manual (SPM), Sections 2.62 and 3.85 (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975). The methods described in Section 3.85 are best applied to beaches with slopes flatter than 1 on 100 (m = 0.01). This report, by applying methods of Section 2.62, presents a method for estimating wave setup for slopes as steep as 1 on 10 (m = 0.10). The work was carried out under the coastal construction program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by John R. Lesnik, Hydraulic Engineer, under the general supervision of R.A. Jachowski, Chief, Coastal Design Criteria Branch, who initially conceived the idea for this technical aid. The author acknowledges Dr. D.L. Harris, whose constructive comments enhanced the utility and clarity of this report.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

John H. Cousins

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.8532	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.
To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

a dimensionless parameter

b dimensionless parameter

d water depth

d_b depth of water at breaking wave

g gravitational acceleration

H_b wave height at breaking (breaker height)

H_o deepwater significant wave height

H'_o deepwater wave height equivalent to observed shallow-water wave unaffected by refraction or friction.

H_s significant wave height $H_{1/3}$; average height of highest one-third of waves for specified time period

L wavelength

L_o deepwater wavelength

m beach slope

S_b wave setdown at breaking zone

S_w net wave setup at shore

ΔS wave setup between breaker zone and shore

T wave period

WAVE SETUP ON A SLOPING BEACH

by
John R. Lesnik

I. INTRODUCTION

Design of coastal structures requires consideration of abnormally high water levels produced by storms. An important component of the storm surge can be the rise in water level produced by wave action.

The wave train approaching the coast and breaking offshore causes the water to pile up on the beach. Depending upon the wave characteristics (height and period) and beach slope, this accumulation of water will continue until the slope of the water surface in the onshore-offshore direction results in a head which balances the forces tending to drive the water onto the beach. This rise in water level is commonly called *wave setup.*

Two conditions that could produce wave setup will be examined in this report. The simplest case is illustrated in Figure 1(a), where the dash-line represents the normal stillwater level (SWL); i.e., the water level that would exist if no wave action were present. The solid line represents the average water level when wave shoaling and breaking occur. A series of waves is shown at an instant in time, illustrating the actual wave breaking and the resultant runup. As the waves approach the shore, the average water level decreases to a minimum at the breaking point, d_b. The difference in elevation between the mean water level (MWL) and the normal SWL at this point is called the *wave setdown*, S_b. Beyond this point, d_b, the MWL rises until it intersects the shoreline. The total rise between these points is the wave setup between the breaking zone and the shore, denoted ΔS. The net wave setup, S_w, is the difference between ΔS and S_b and is the rise in the water surface at the shore above the normal SWL. In this case, the wave runup, R, is equal to the greatest height above normal (SWL) which is reached by the uprush of the waves breaking on the shore. For this type of problem, the runup, R, includes the setup component and a separate computation for S_w is not needed. The reason for this is that laboratory measurements of wave runup are taken in reference to the SWL and already include the wave setup component.

Figure 1(b) illustrates a more complex situation involving wave setup on a beach fronted by a wide shelf. At some distance offshore the shelf abruptly drops off to deep water. As waves approach the beach, the larger waves in the spectrum begin to break at the seaward edge of the shelf and a setup is produced. The increase in water level produced by this setup allows larger waves to travel toward shore until they break on the beach. Runup calculations performed at that point would include setup effects from the breaking of these waves.

Calculation of the precise value of the wave setup for all conditions is a formidable problem for which a satisfactory solution is not yet

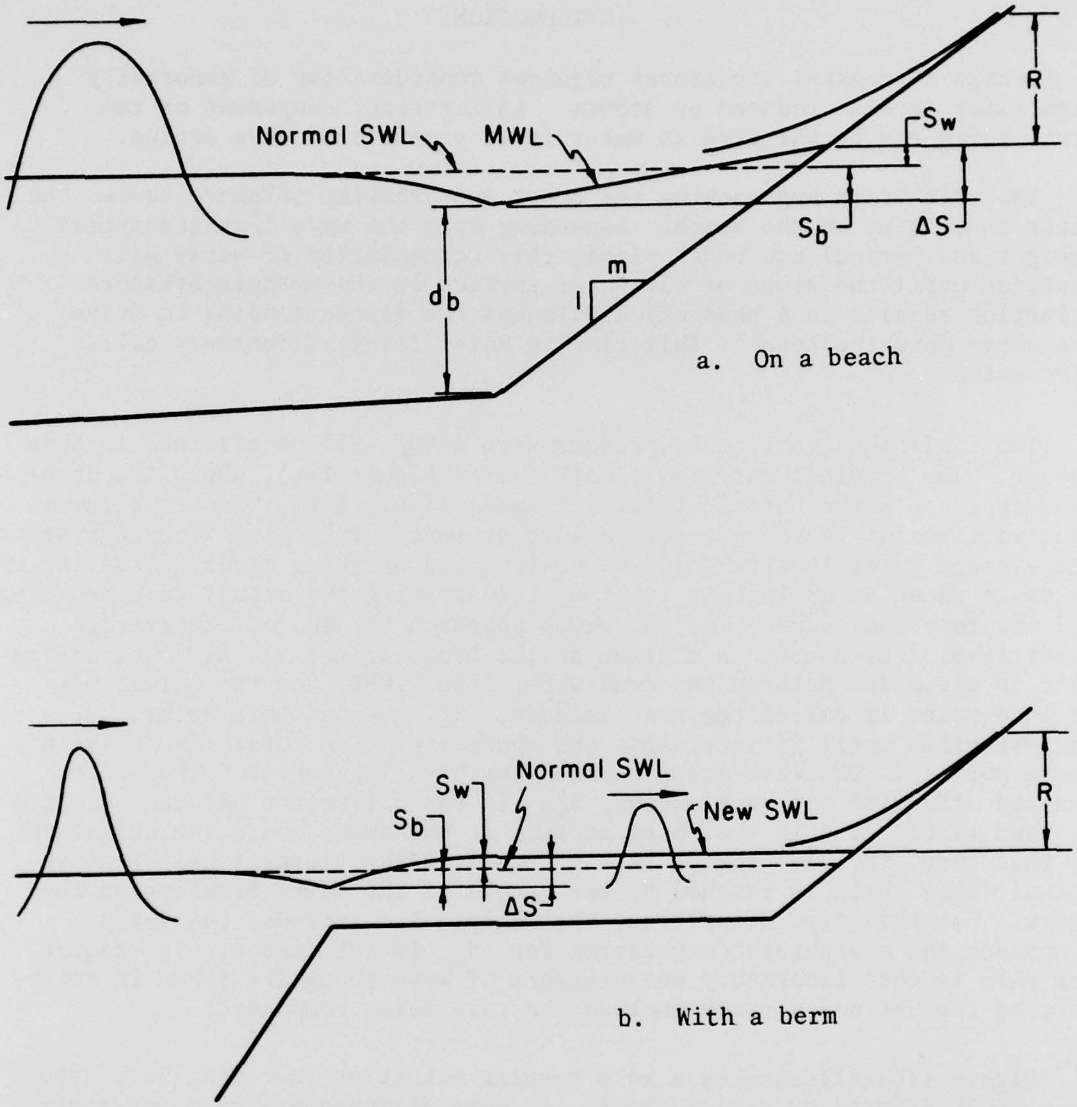

Figure 1. Definition sketch of wave setup.

available. The problem can be greatly simplified through an idealization which leads to a satisfactory estimate of the upper limit of this effect for many practical problems. Fortunately, the upper limit of the wave setup is of greatest importance in most design problems.

When waves, coming from deep water, are dissipated on the beach without refraction, the kinetic energy of the waves is converted to the potential energy of wave setup, and the kinetic energy of longshore currents and turbulence. The wave setup component is maximized by neglecting the longshore currents and turbulence. This situation exists in many laboratory wave tanks and on beaches where the bottom contours are approximately parallel to the beach and the waves approach along a line normal to the shore. At most locations, it is also possible for the extreme waves to approach along a line normal to the shore. Where this is not true, a conservative upper limit can generally be obtained by multiplying the value obtained by the procedure given in Section II by the cosine of the angle between the wave crest outside the breaker zone and the shoreline.

Where bottom contours are not approximately parallel to the shore, the estimates (Sec. II) will tend to be too large for regions of diverging wave rays and too small for regions of converging wave rays.

A more complex analysis involving refraction analysis and a solution of the radiation stress equations is expected to provide essentially the same answer as the procedures given in Section II where bottom contours are nearly parallel to the shore and the waves approach along a line nearly normal to the shore. When the waves undergo significant refraction over parallel bottom contours, the more detailed calculations are expected to yield lower values. Additional development is needed to provide satisfactory procedures for computing wave setup in regions with complex bathymetry.

This report provides the designer with a simplified method of estimating wave setup on a sloping beach. Section 3.85 of the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975) provides a method for estimating wave setup assuming $d_b = 1.28\ H_b$. This assumption best applies to relatively flat beaches ($m < 0.01$) with breaker steepness (H_b/gT^2) values less than 0.01.

A method for relating d_b to H_b for sloping beaches is given in the SPM (Sec. 2.62). By applying these relationships to the method for estimating wave setup, a family of curves is developed that defines the net wave setup for the breaker height, H_b, and the period, T, for any breaker steepness or beach slope.

The computation of wave setup can be an important part of a thorough design effort requiring water level estimation. For major engineering structures such as nuclear powerplants, it is quite important to consider all possible causes of water level rise. Wave runup computations alone will usually be sufficient, but in cases similar to that shown in Figure 1(b), where large waves break offshore, an initial adjustment to the SWL

will be necessary to consider the wave setup caused by these breaking waves.

In studies of coastal flooding by hurricanes, the engineer could choose to include the effects of wave setup in the water level estimate. This report could be used to compute that setup for both cases (Fig. 1) where runup values are not desired.

Additional methods for estimating wave setup are given in James (1974) and Goda (1975). Application of these methods is not discussed in this report.

II. EQUATIONS

All equations in this memorandum have been previously presented in the SPM. Equation 3-48 of the SPM shows that the net wave setup on a shoreline is the algebraic sum of the wave setup and wave setdown, or

$$S_w = \Delta S + S_b \ , \tag{1}$$

where S_w is the net setup, ΔS is the wave setup, and S_b is the wave setdown; S_b is defined as a negative value.

Equation 3-46 of the SPM defines the setdown, S_b, as

$$S_b = - \frac{g^{1/2} \ (H_o')^2 \ T}{64\pi \ d_b^{\ 3/2}} \ , \tag{2}$$

where

g = gravitational acceleration,

H_o' = equivalent unrefracted deepwater wave height,

T = wave period,

d_b = depth of water at breaking wave.

Note that $H_o' = H_o K_R$, and where $K_R = 1$, $H_o' = H_o$.

Equations 2-91, 2-92, and 2-93 of the SPM define d_b in terms of the breaker height, H_b, period, T, and beach slope, m.

$$d_b = \frac{H_b}{b - \left(a \dfrac{H_b}{gT^2}\right)} \ , \tag{3}$$

where a and b are approximately:

$$a = 43.75\ (1 - e^{-19m}) \tag{4}$$

$$b = \frac{1.56}{1 + e^{-19.5m}}\ . \tag{5}$$

Values of d_b from equation (3) can then be used in equation (2) when defining the wave setdown.

Equation (2) uses the equivalent unrefracted deepwater wave height, H_o', rather than the breaker height, H_b. Figure 2 gives values of H_b/H_o' in terms of m and H_o'/gT^2.

Longuet-Higgins and Stewart (1963) have shown from an analysis of Saville's (1961) data that,

$$\Delta S = 0.15\ d_b\ \text{(approximately)}\ . \tag{6}$$

Combining equations (1) to (6) gives

$$S_w = 0.15\ d_b - \frac{g^{1/2}\ (H_o')^2\ T}{64\pi\ d_b^{\ 3/2}}\ , \tag{7}$$

where

$$d_b = \frac{H_b}{\dfrac{1.56}{1 + e^{-19.5m}} - 43.75\ (1 - e^{-19m})\ \dfrac{H_b}{gT^2}}\ . \tag{8}$$

Figure 3 plots equation (7) in terms of S_w/H_b versus H_b/gT^2 for slopes of m = 0.02, 0.033, 0.05, and 0.10, and is limited to values of $0.0006 < H_b/gT^2 < 0.027$.

Wave setup is a phenomenon involving the action of a train of many waves over a sufficient period of time to establish an equilibrium water level condition. The exact amount of time for equilibrium to be established is unknown but a duration of 1 hour is considered as an appropriate minimum value. The very high waves in the spectrum are too infrequent to make a significant contribution in establishing wave setup. For this reason, the significant wave height, H_s, represents the condition most suitable for design purposes.

The designer is cautioned not to confuse the wave setup with wave runup. If an estimate of the highest point reached by water on the shore

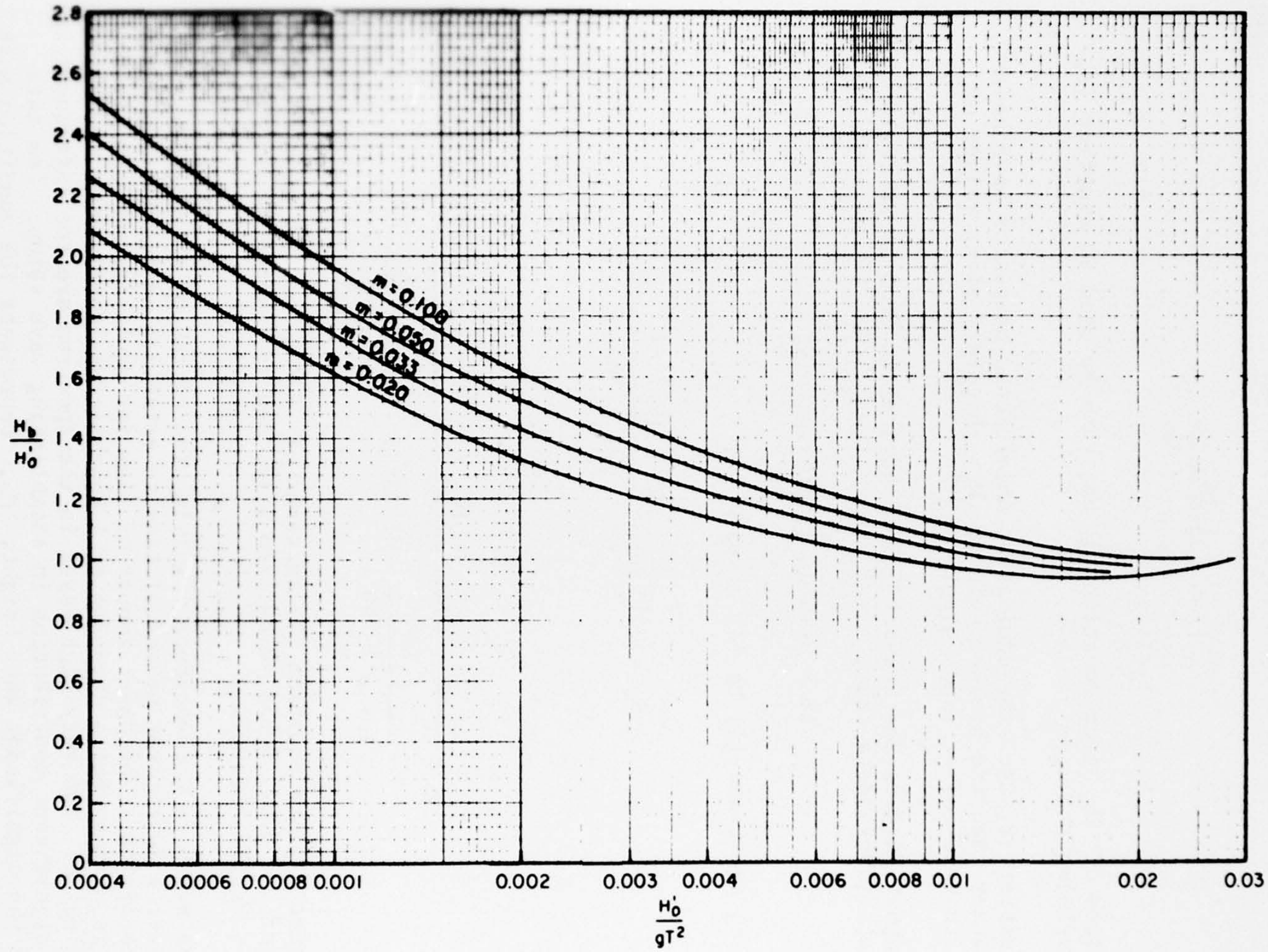

Figure 2. Breaker height index, H_b/H_o' versus deepwater wave steepness, H_o'/gT^2. (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975)

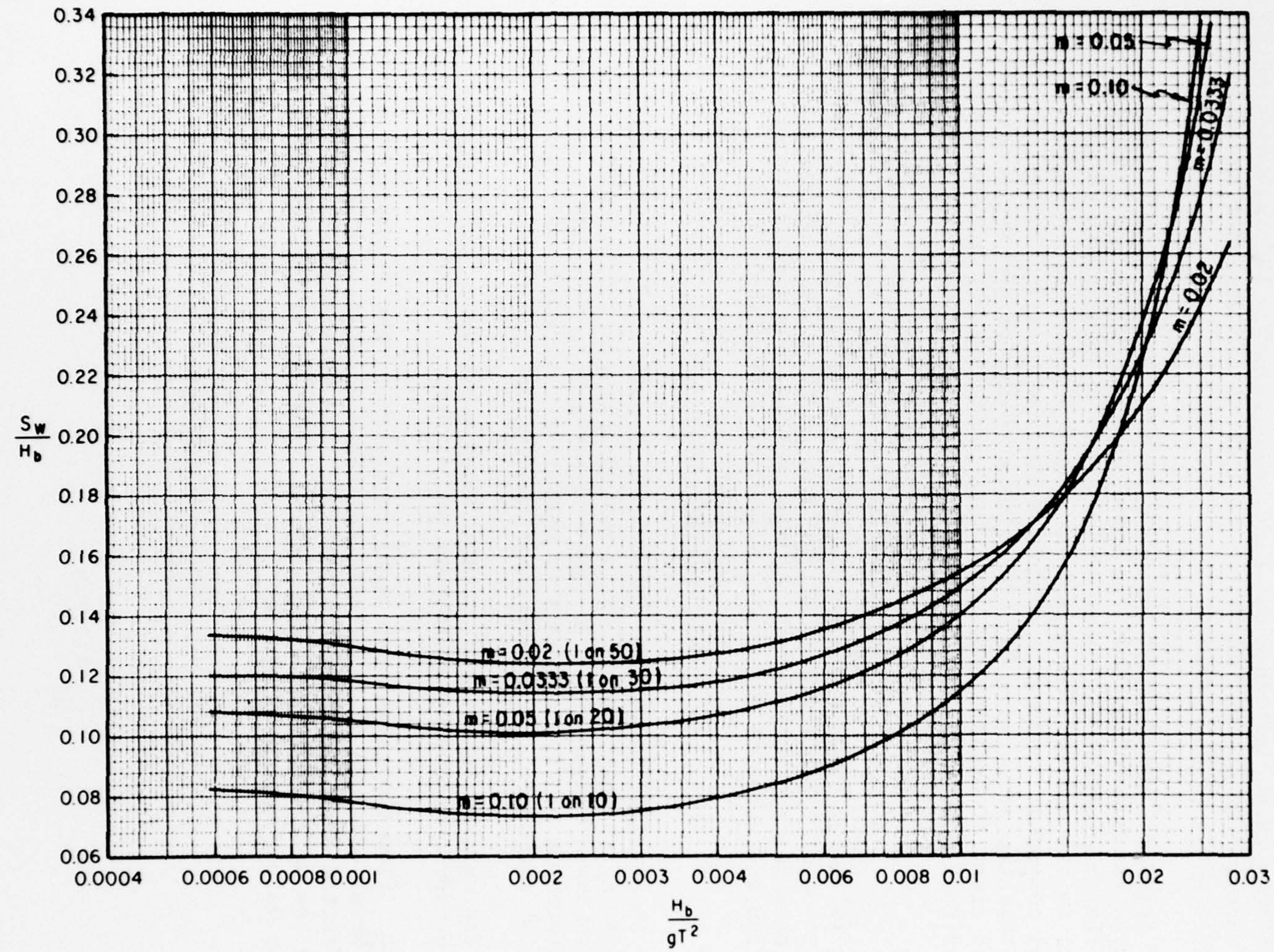

Figure 3. S_w/H_b versus H_b/gT^2.

is desired, the runup produced by a larger design wave can be estimated after considering the water level produced by wave setup (using H_s) and other effects (e.g., astronomical tide, wind setup). The selection of a design wave for runup considerations is left to the designer based upon the requirements of the project.

The setup estimates using the methods described in this report are based upon the assumption that the waves approach normal to the coast. A wave that approaches the coast at an angle has components normal and parallel to the coast. The normal component produces wave setup, the parallel component produces a longshore current. It is reasonable to assume that the setup is a function of the cosine of the angle between the wave crest at breaking and the shore. Reducing the estimated wave setup in this manner is left to the judgment of the designer.

III. SAMPLE DESIGN PROBLEMS

The following examples show the use of the techniques presented in the solution of typical design situations. Refer to the SPM for other information related to the total design problem (e.g., wave theory, refraction analysis, tides, storm surges, wave breaking).

* * * * * * * * * * * * * * * EXAMPLE PROBLEM 1 * * * * * * * * * * * * * * *

GIVEN: A wave gage is located in 22 feet of water at MLW (see Fig. 4). Analysis of the gage record for a period during a storm yields a significant wave height, H_s = 20 feet and period, T_s = 12 seconds. Assume the direction of wave approach is normal to a straight coast with parallel contours (i.e., refraction coefficient = 1.0).

FIND: The maximum water level at the beach where runup calculations can be made considering an initial SWL at MLW.

SOLUTION: From the given conditions in Figure 4, the significant wave will break offshore of the shelf and induce a setup. First, define the unrefracted deepwater wave height, H'_o, and the breaker height, H_b. Using the methods given in SPM (App. C, Table C-1), the following wave height values were obtained for

$$\frac{d}{L_o} = \frac{22}{5.12(12)^2} = 0.02984$$

$$\frac{H}{H'_o} = 1.126$$

$$H'_o = 17.76 \text{ feet}$$

by referring to Figure 2 with m = 0.05, and

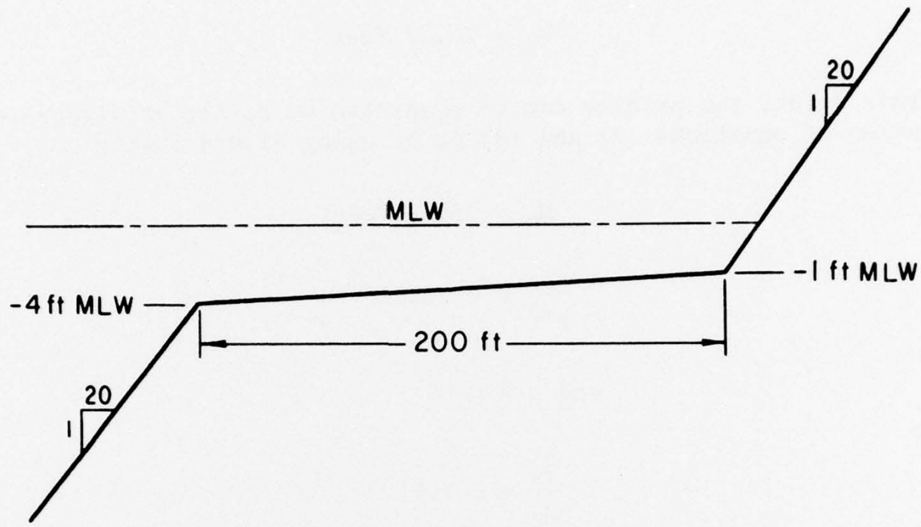

Figure 4. Definition sketch for example problem 1.

$$\frac{H_o'}{gT^2} = 0.003830$$

$$\frac{H_b}{H_o'} = 1.31$$

$$H_b = 23.27 \text{ feet} \quad .$$

At this point, the problem can be completed by either an algebraic solution of equations (7) and (8) or by using Figure 3 with

$$H_b = 23.27 \text{ feet}$$

$$\frac{H_b}{gT^2} = 0.005019$$

$$\text{and } m = 0.05 \quad ,$$

then

$$\frac{S_w}{H_b} = 0.111$$

or

$$S_w = 2.58 \text{ feet}$$

$$S_w = 2.6 \text{ feet}$$

Therefore, the new water level at the beach will be +2.6 feet MLW, which will result in a depth of 3.6 feet at the toe of the beach slope. The computation of the maximum runup height on the beach would involve the determination of the maximum breaking wave and runup for a range of wave periods. The highest runup elevation computed would be used for design purposes.

* * * * * * * * * * * * * * EXAMPLE PROBLEM 2 * * * * * * * * * * * * * *

GIVEN: A mathematical model simulation indicates that a particular section of coastline will experience a storm surge of +15 feet for a particular hurricane. The backshore area is protected by a continuous line of sand dunes whose lowest elevation is at about +20 feet. An estimate of the deepwater significant wave height and period yields H_o = 30 feet and T_s = 12 seconds. The beach slope is a constant m = 0.05.

FIND: Whether continuous flooding of the backshore can be expected when wave setup is considered.

SOLUTION: In this case, assume that $H_o = H'_o$. Then, H_b can be found from Figure 2 with

$$\frac{H'_o}{gT^2} = 0.00647$$

and $$m = 0.05 \quad ;$$

thus, $$\frac{H_b}{H'_o} = 1.16$$

or $$H_b = 34.80 \text{ feet} \ .$$

From Figure 3, with $$H_b = 34.80 \text{ feet}$$

$$\frac{H_b}{gT^2} = 0.007505$$

and $$m = 0.05 \quad ;$$

thus, $$\frac{S_w}{H_b} = 0.124$$

or $$S_w = 4.3 \text{ feet} \quad .$$

Therefore, the MWL will be at elevation +19.3 feet which is 0.7 feet below the top of the dunes. Extensive flooding should be expected. If desired, Section 7.22 of the SPM could be used to estimate the quantity of flow over the dune.

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